Coherent electron Cooling
Proof of Principle

Instrumentation

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MAC Review
8-10 December 2014

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

Introduction

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Energy Spread Measurement

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FEL IR Instrumentation

Intensity measurement

Transverse Profile measurement

Spectral Analysis

RHIC Instrumentation

Wall Current Monitor

BPM's, Schottky

Summary

Installation location RHIC Sector 2

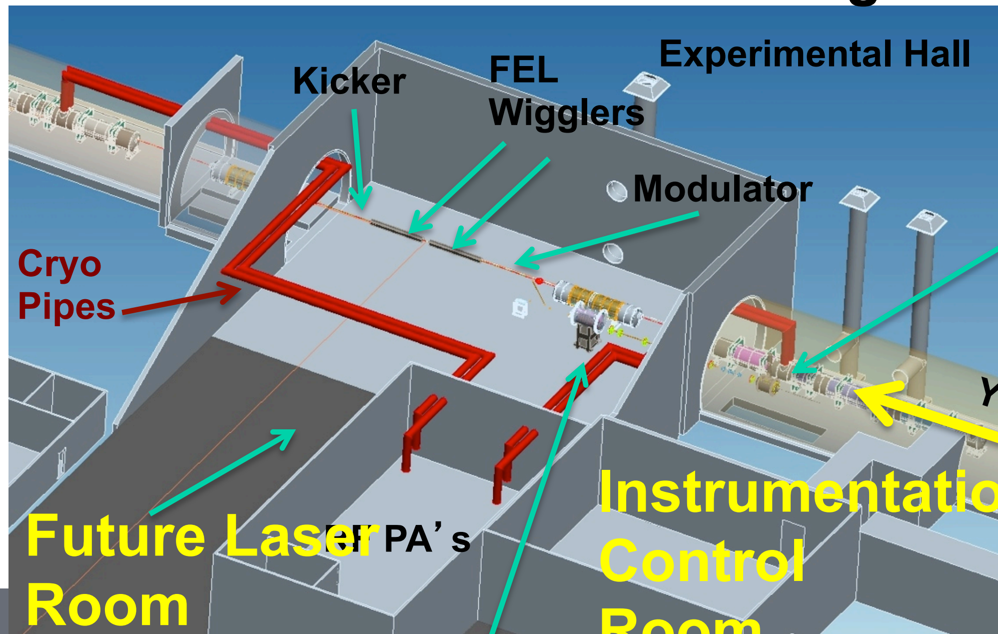
CeC PoP Facility Layout

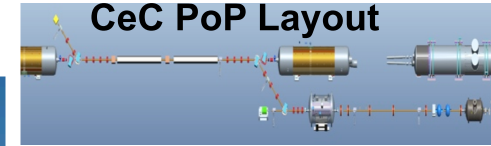
Same Layout,
4 views

Just fits in without moving any RHIC magnets.

Cable runs on the order of 200-300'

RHIC Sector 2 Interaction Region

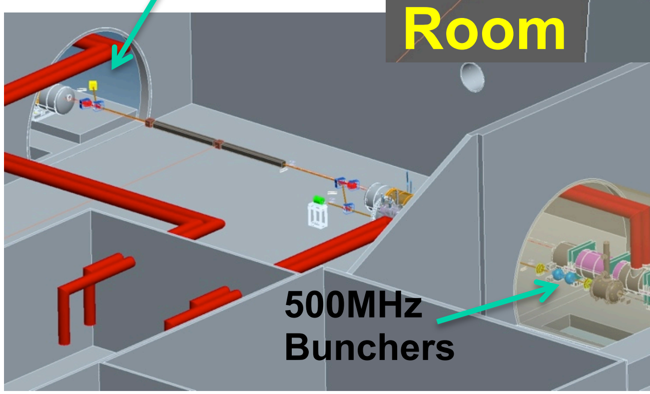




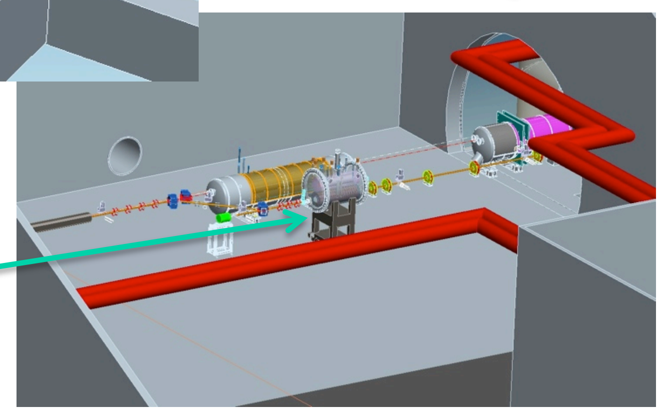
SC Gun

Yellow RHIC Beam

Beam Dump



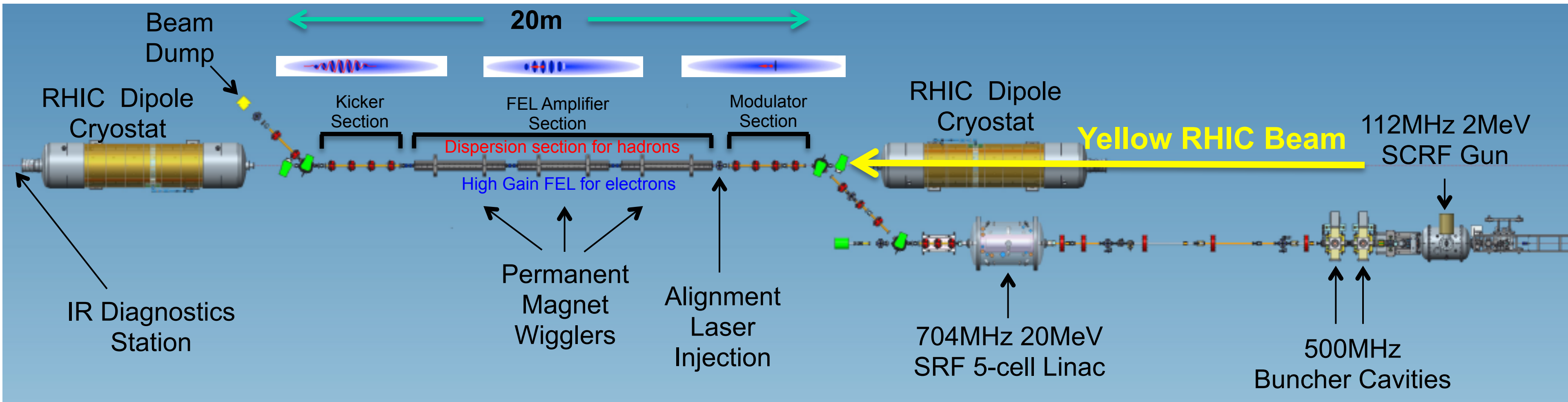
Superconducting Linac



Electron Beam Transport Overview

RHIC Sector 2 IR

RHIC 40GeV/n AU and 22MeV electron Merger location



Goal of Diagnostics:
Electron trajectory alignment for lasing

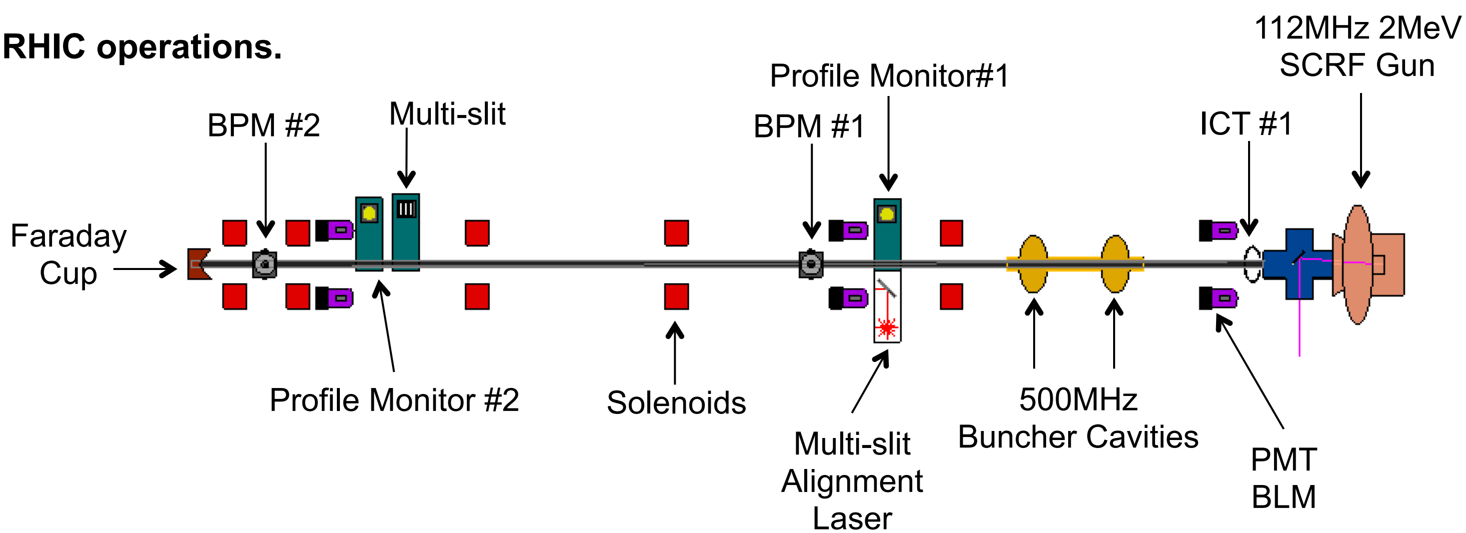
"Proof of principle"
Minimal but sufficient diagnostics provided

Layout for Phases 1 & 2

- **Phase 1: Test of the Gun & SRF cavity, measuring dark current with**
  - Profile Monitor
  - BLMs
- **Phase 2: Test with cathode & laser to produce beam, measuring with**
  - BPMs
  - Profile Monitors
  - BLMs
  - ICT (Current Monitor)
  - Faraday Cup
  - Emittance measured with multi-slit mask and Profile Monitor
- **Test independent of RHIC operations.**

Instrumentation:

ICT = 1
BPM = 2
Profile Mon = 2
Slit Mask = 1
PMT BLM = 6
Faraday Cup = 1

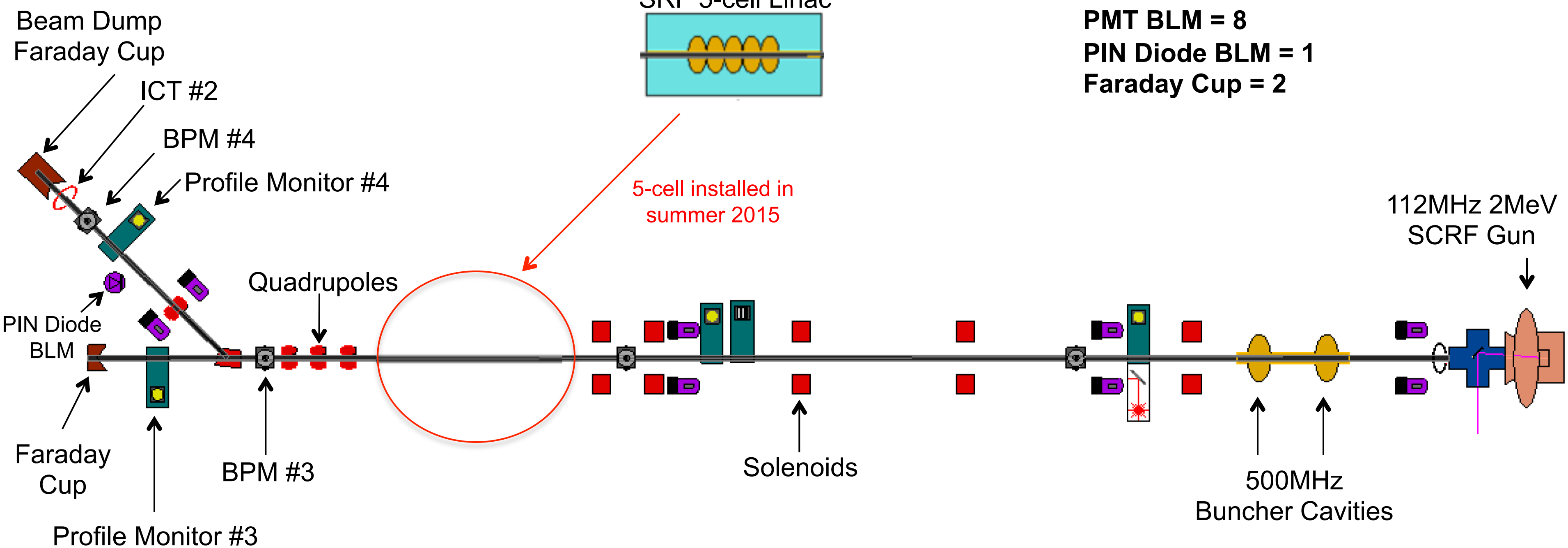


Layout of Phase 2.1

- Addition of the 5-Cell and dog-leg injection line, repeat phase 1 measurements with higher energy beam.
- Test independent of RHIC operations.

Instrumentation:

ICT = 2
BPM = 4
Profile Mon = 4
Slit Mask = 1
PMT BLM = 8
PIN Diode BLM = 1
Faraday Cup = 2



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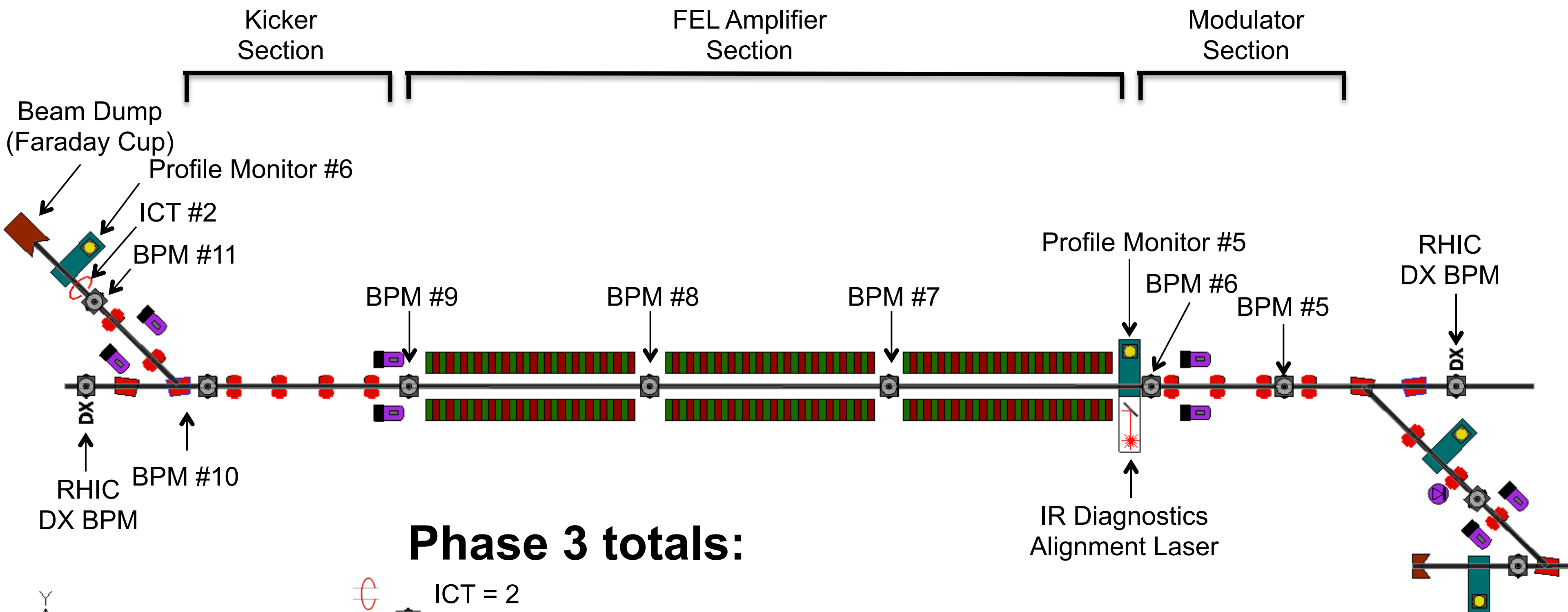
Layout of Additions for Phase 3



Phase 3 totals:

- ICT = 2
- BPM = 11
- Profile Mon = 6
- Slit Mask = 1
- PMT BLM = 14
- PIN Diode BLM = 4
- Faraday Cup = 2

Electron Beam Parameters

ELECTRON BEAM PARAMETERS	
Energy	2 & 22 MeV
Charge per bunch	0.5 – 5 nC
Electrons per bunch	3 – 6×10^9
E-beam current (1nC)	78 μA
Repetition rate	78 kHz
RMS Normalized Emittance	< 5 mm•mrad
RMS energy spread	$<1 \times 10^{-3}$
RMS bunch length	10 psec
RMS transverse beam size	1 mm
E-beam power	1.7 kW

Design and installation challenges due to SC gun and Linac:

- 10^{-11} torr vacuum
- 200C bake
- Particulate processing, class 100 near SC cavities

Instrumentation Parameters

Measurement		Required Resolution/ Accuracy	Instrument Resolution/ Accuracy	Method	Notes
2 to 22 MeV e-beam transport instrumentation parameters					
Electron Beam Position		30µm/ 100µm	10µm/ 50µm	BPMs (15mm buttons) Dual plane stations	Reuse Libera's from ERL, these have 703MHz BP filters, averaged data, not bunch-by-bunch
Cooling Section Beam Position	**Electrons**	30µm/ 100µm	10µm/ 50µm	BPMs with ***SHARED*** 15mm buttons Dual plane stations	BNL Zync Electronics VME boards ring **700MHz** front-end filter for averaging over many electron bunches
	Ions	100µm/ 100µm	10µm/ 50µm	BPMs with ***SHARED*** 15mm buttons Dual plane stations	BNL Zync Electronics VME boards ring **39MHz** front-end filter for averaging over many ion bunches
Transverse Profile		100µm (10% of 1 mm beam)	50µm	YAG screen & CCD *Measured at low power*	25mm YAG:Ce crystal with 2MP CCD GigE camera for 39px/mm resolution
Bunch Charge		5%/1%	1-10 pC noise floor	Integrating Current Transformer	Bergoz ICT, BCM-IHR. Expect bunch charge 0.5-5nC 0.1 – 7µs integration window @ 10kHz max rep rate
Beam Current		1µA	(TBD)	Dump Faraday Cup	Isolated dump as a Faraday Cup.
Beam Loss		10µA Loss limit	1µA	PMT detectors with JLAB VME electronics	Designed for a sensitivity of 0.1 – 6 µA of beam loss and an integrated trip limit of 10 – 60 µA•ms
Emittance		10%	10%	Plunging multi-slit mask & Profile Monitor	Two position mask, Horizontal & Vertical slits
Energy Spread		$<1\times10^{-3}$	1% of max $\Delta p/p$	YAG in dispersive section	Based on 1mm beam size and 4X horizontal beam size growth under max $\Delta p/p$

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Summary

Integrating Current Transformer

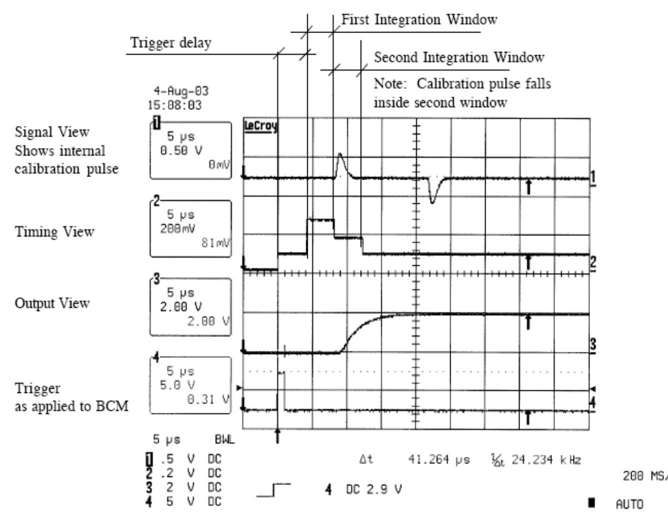
For making periodic measurements of bunches or bunch trains from 0.1us to 7µs long, located downstream of the gun, and at dump.

<u>Bergoz</u> ICT-CF6-60.4-070-05:1-H-UHV-THERMOE

Integrating type, In-flange CT

- Bergoz BCM-IHR electronics
- 10kHz option
- Background Subtract
- Noise floor 1-10 pC
- Calibrated

Signal processing timing diagram: Gate width <0.1us up to >7us



<u>Mechanical details:</u>

60.4mm ID

40mm axial length

Rad-Hard option

Bakeable to 180C

- Separate bake-out zone
- Internal TC, type-E

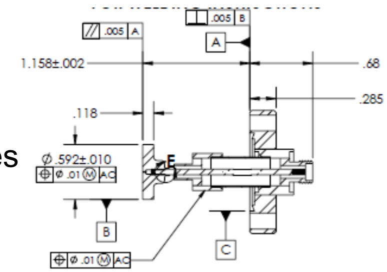
<u>Requirements for bunch charge at 0.5-5nC:</u>

5% accuracy

1% resolution

Beam Position Monitors – Pick-ups & Electronics

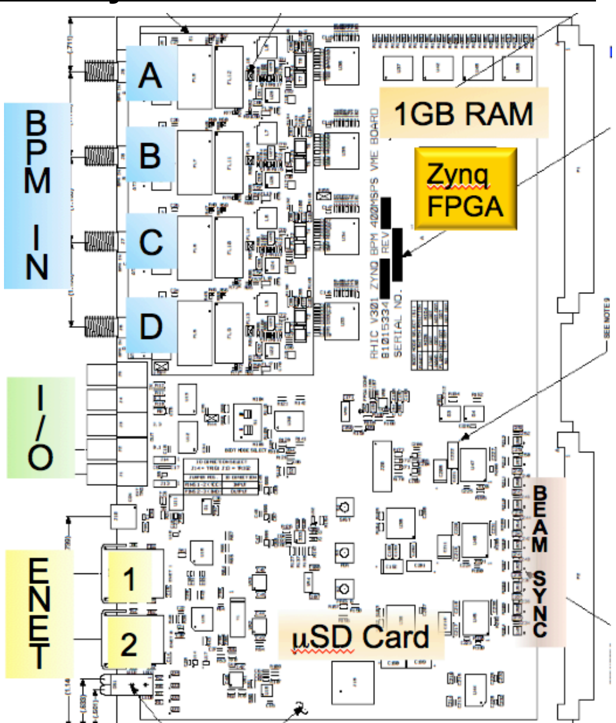
Dual-plane button pick-ups
- 11 locations (2 at 2MeV, 9 at 22MeV)
- 15 mm diameter molybdenum button's
- MPF Inc PN: A9111-2-CF
  - SMA Connector, SS housing & 4.5" CF flanges



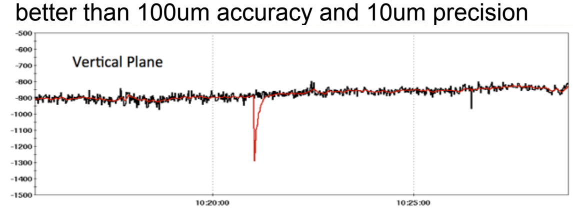
BPM 15mm button

BPM Pick-up housing

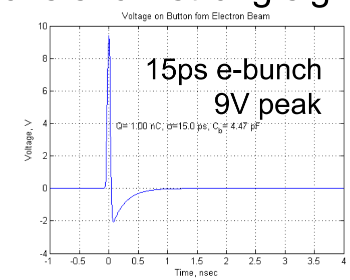
BNL Zync electronics VME board:

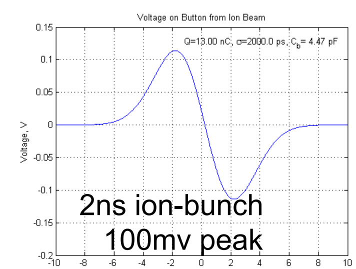


- VME Form Factor
  - Use RHIC Controls Infrastructure
- Configurable RF Section
  - Hadron or Electron Beam Options
- 4 x 400MSPS A/D Converters
  - 2 Planes of Measurement / Board
- Integrated Front End Computer
  - FEC & FPGA on Single Chip (Zynq)
- Ethernet Connectivity (x2)
  - Controls Network
  - High Speed Interface for Feedback
- Test results below at the ATF with buttons showed better than 100um accuracy and 10um precision



Simulations show strong signals

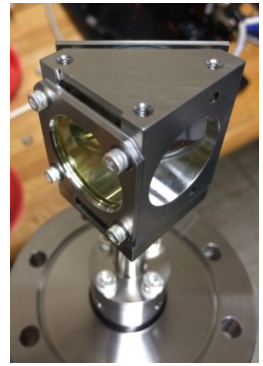


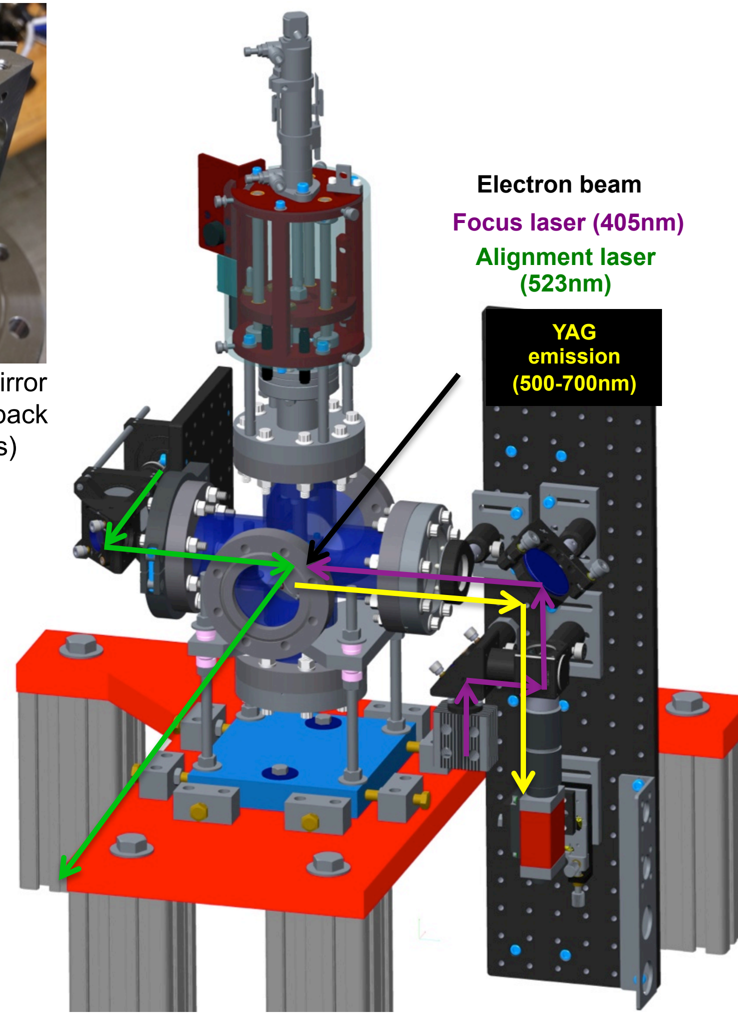


Transverse Profile Monitor

BNL Design

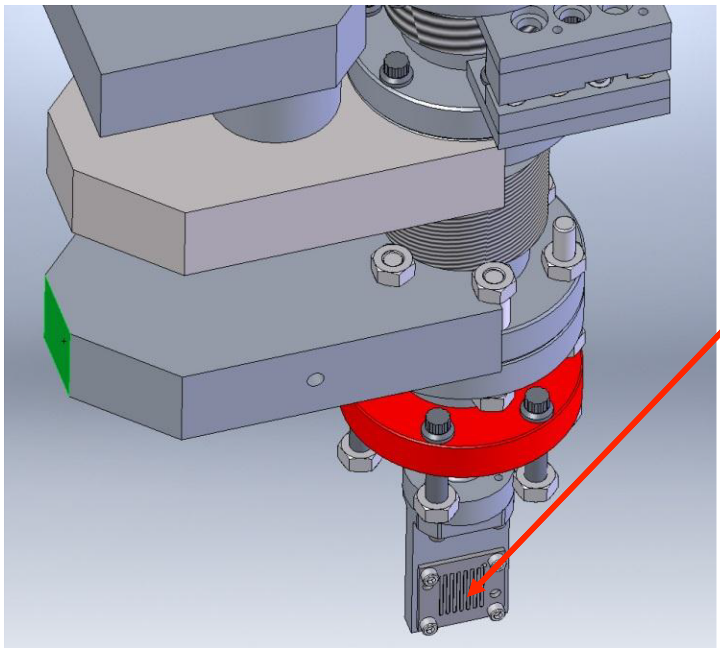
- YAG:Ce crystal, (100μm thick)
- Normal to beam; copper mirror behind crystal
- 25mm aperture
- Two position pneumatic plunger
- 2MP GigE camera (model "Manta" by AVT)
- 50mm fixed lens
- Tested to better than 50μm optical resolution
- Actuator separable from UHV linear motion feed through
- Laser focus assist
  - 405nm laser injected through dichroic beam splitter to excite YAG for focusing
  - 450nm Longpass edge filter protects CCD from backscattered 405nm light.
- Alignment laser for downstream multi-slit uses backside mirror on YAG holder.

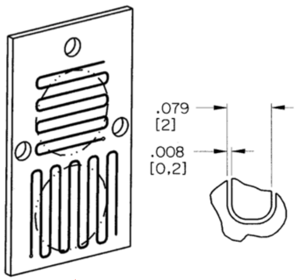

YAG crystal & mirror holder (back-to-back copper mirrors)

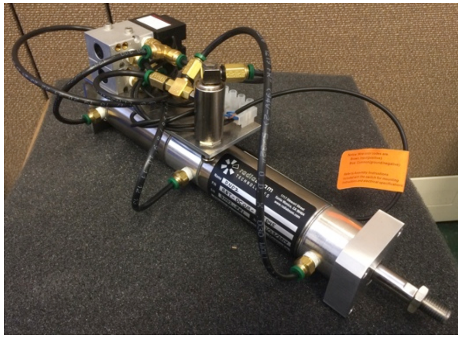


Emittance Slit Measurement
- Transfer from ERL (need new mask)

- Low Power Operations Only
- Positioned 0.35 m upstream of profile monitor
- Tungsten Slit mask, optimized expected emittance:
    - 10 slits, 2mm separation, 200μm width in 1.5mm thick.
- New Dual axis design for Horizontal & Vertical measurement
- Replaces single axis mask originally installed.







Dual Station Actuator retrofitted for new dual axis mask.

ANALYSIS:
An algorithm was developed for analyzing the image from a multi-slit mask for emittance measurement.

Future plans are to automate the image analysis for on-line processing and data logging.

Intensity Distribution at mask

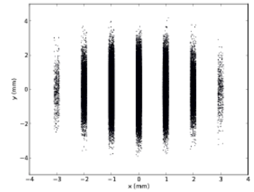
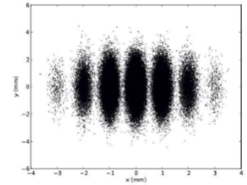
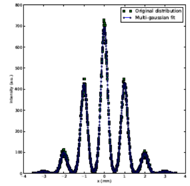


Image on profile monitor after drift distance



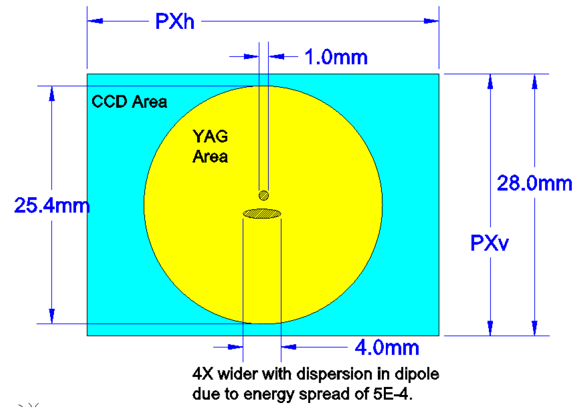


Energy Spread Measurements

- Max. Energy Spread: 5×10^{-4}
- Beam Size (d): 1mm (dia.)
- Dispersion after *dipole & quad*
- $\sigma_{\delta\text{-}H}$ expected to be 4mm in dog-leg section
- Δ Beam Size $_H$: (4 – 1 mm) x 34.4px/mm ≈ 100px
  - $\sigma_{\delta\text{-}H}$ spread over 100 pixels

  ➔Resolution: 1% of max $\Delta p/p$

Image of 25.4mm YAG as projected onto CCD



- Camera resolution: 2MP
  - 1292 X 964 pixels

  (px_h X px_v)
- $\text{Pitch}_{YAG} = W_{CCD}/px_v$

  = 964px/28mm

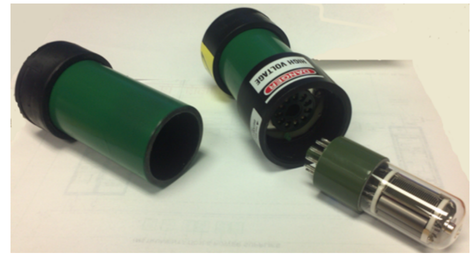
  =34.4px/mm

  = 30um/px

Loss Monitors

Beam Loss Monitors

- **PMT Detector** (similar to JLAB-CEBAF, FEL)
- (Hamamatsu R11558 PMT)
- Fast (<<1us), HV tunable for sensitivity adjustments
- 50dB DR (5nA – 100uA from tube)
- Limited coverage, small cross section



BLM Electronics

- The new version of BLM electronics developed at JLAB
- Dual response:
  - Linear response for beam loss protection
  - Logarithmic response for instrumentation
- Two 8-ch modules installed support 14 PMT BLMs
- Designed for sensitivity to 0.1 – 6μA beam loss and 10 – 60 μA•μs integrated trip limit.
- Controls integration is underway.

Features:

- Provide both machine protection and diagnostic functions.
- Instantaneous readback of beam loss.
- 16 bit digital output for integrating and logarithmic signals.
- Fast response, << 1 μs response time for integrating, 10 nA^2 for log.
- Wide dynamic range (>50 dB) for logarithmic signals.
- Built-in self test and onboard signal injection.
- FPGA controlled.
- Local data buffer for integrating and logarithmic signals.
- VME interface and fully integrated into EPICS.
- Pulse beam measurement and continuous monitoring.
- Low cost (≤$100 per channel).

New Beam Loss Monitor for 12GeV Upgrade
J. Yan, K. Mhoney, ICALEPCS 2009a

Infrared Camera (FLIR A310)

Check for beam pipe heating, or losses other detectors can't see.

Remote image display & storage, Ethernet communication.

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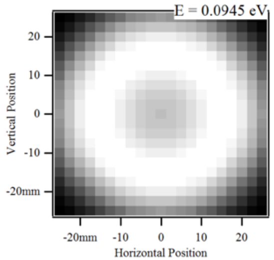
Summary

Infrared Diagnostics Layout for Wiggler Light

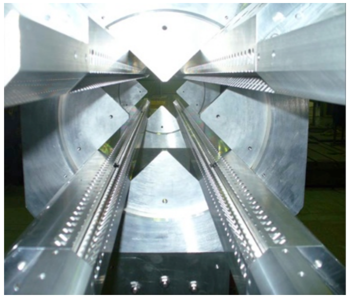
IR Diagnostics include:
- Power (over two ranges)
- Transverse profile
- Spectral Analysis

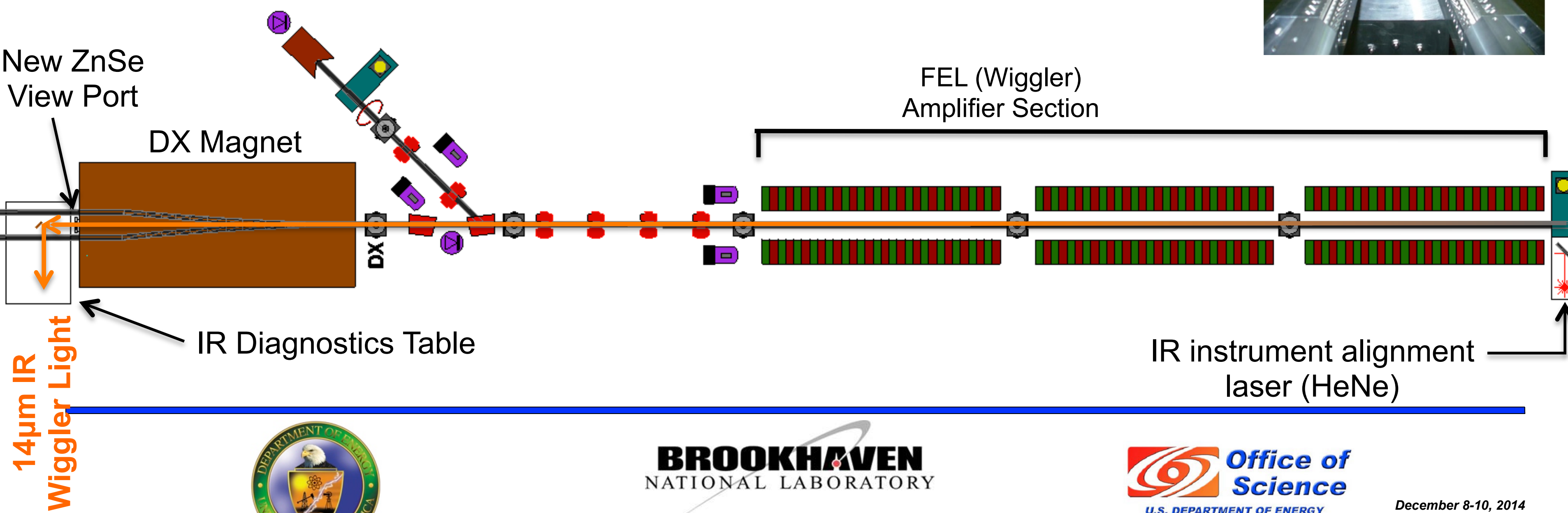


Simulations predict a 40mm radiation pattern at 15m from the FEL.

Wiggler Parameters	Value
Length (3 sections)	3 x 2.8 m
Period (λ_u) / poles	4 cm / 3 x 60 + 2.5 (match)
Strength (K)	0.50
Wavelength	14 μm
Optical Power	250 nW – 250 mW

Permanent magnet wigglers (three) built by the Budker Institute, 32mm gap, 0.134T peak filed, 60 poles over principle length of 2.5m (+2.5 matching poles, over 30cm)



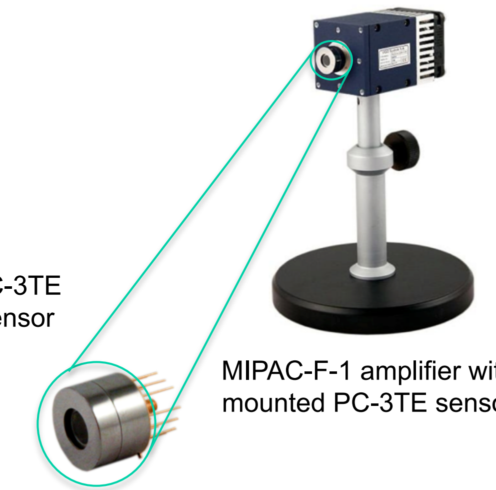


Wiggler Light Intensity Measurement

Change in the wiggler light intensity is a direct indication of FEL amplification, necessary for coherent cooling.

- HBW Low Intensity IR Photodetector:
  - Used to resolve variations from pulse to pulse in the 78kHz beam
  - Sensitivity as low as 1μW over 2 – 14μm
  - BW up to 1MHz
  - TE cooled (HgCd)Te detector under GaAs lens
  - May employ lock-in amplifier to improve S/N ratio at 78kHz
- Thermal Power sensor
  - Used to measure average power in CW mode (T_{resp} = 1.8s)
  - 10μW – 3W, over 3 selectable ranges
  - Sensitivity over 0.19 – 20μm through a 9.5mm aperture
  - 1.8 second response time

PC-3TE sensor



MIPAC-F-1 amplifier with mounted PC-3TE sensor

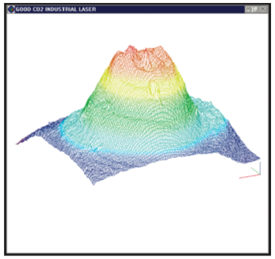
Model 3A thermal power sensor

Wiggler Light Transverse Profile

The profile of the FEL radiation beam is a good indication of the position of the electron beam and is expected to exhibit signs of when the electron and ion beams overlap. **Two methods of instrumentation:**

- **Pyrocam™ IV sensor array:**
  - **Pyroelectric crystal integrating sensor**
  - **100nm – 100µm sensitivity**
  - **320 x 320 pixels on a 25 x 25 mm sensor**
  - **Responds to short pulses, uses a chopper in CW mode**

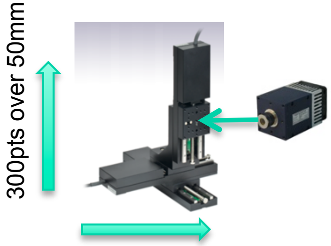
Pyrocam™ IV with pyroelectric sensor array

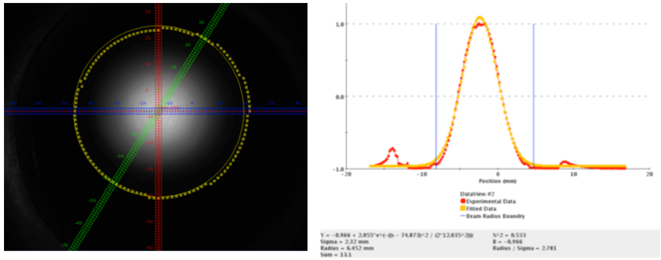


Sample image benefits from the 100 kilo-pixels over 1 in^2 sensor yields a spatial resolution of 12.8 pixels/mm

- **Scanned Profile Measurement**
  - **Low cost motorized stage for photodetector with pinhole mask**
  - **Fast response of the photodetector provides full scan in ~30sec.**
  - **Existing technique used at eLens for direct eBeam transverse profile scan**

IR photo-conductive detector with 0.1mm Pinhole mask



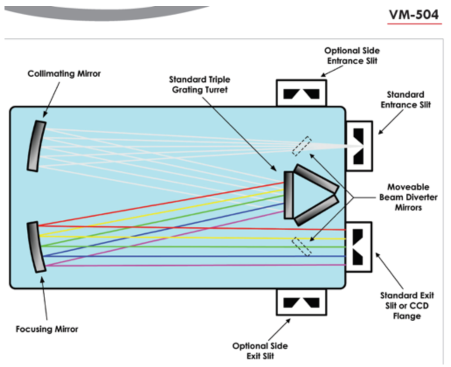


Example image reconstruction & analysis from X-Y array of intensity data points (courtesy of RHIC Electron Lens Pinhole Scanning Profiler)

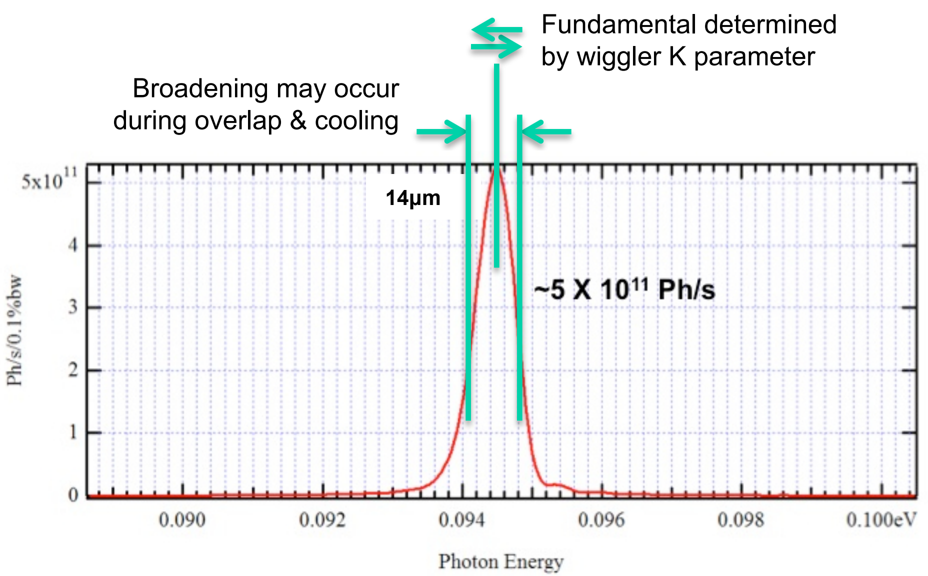
Wiggler Light Spectral Analysis

We expect to see variations in the spectral line width during the cooling process.

Acton VM-504 Spectrometer from Princeton Instruments.



- Acton VM-504 Spectrometer:
  - Made by Princeton Instruments
  - 75-groove/mm grating, centered around 14μm wavelength



- For spectral analysis over the transverse plane:
  - Princeton's imaging spectrograph, model SCT 320
  - Zero astigmatism yields high resolution

Outline

RHIC Ion Diagnostics for CeC PoP

1. Align one ion beam through the Cooler

Use existing RHIC instrumentation routinely used for aligning colliding ion beams

- "DX BPMs" are located upstream and downstream of the CeC beam line.
10's of microns resolution, average orbit

- Orbit stability feedback loops ensure beam position during the store.

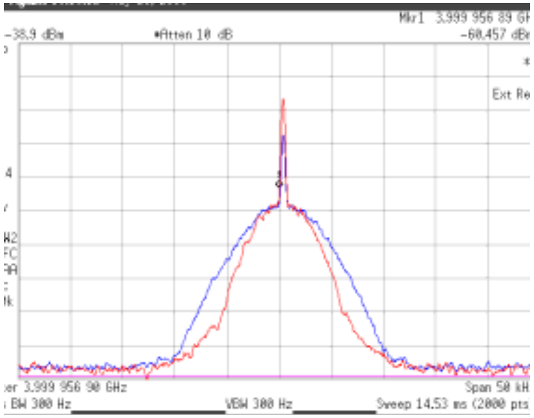
2. Measure Cooling Progress

Use methods developed for successful Stochastic Cooling

Schottky Pick-ups

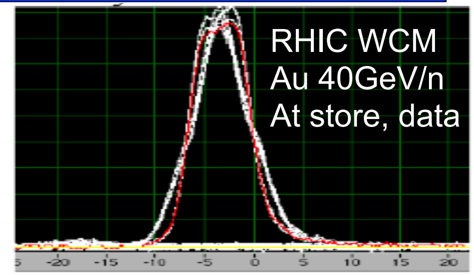
Wall Current Monitor (see next slide)
3KHz -6GHz BW

Anti-cooling: **See when things go bad**
IPM's will see transverse effects
Watch loss monitors carefully

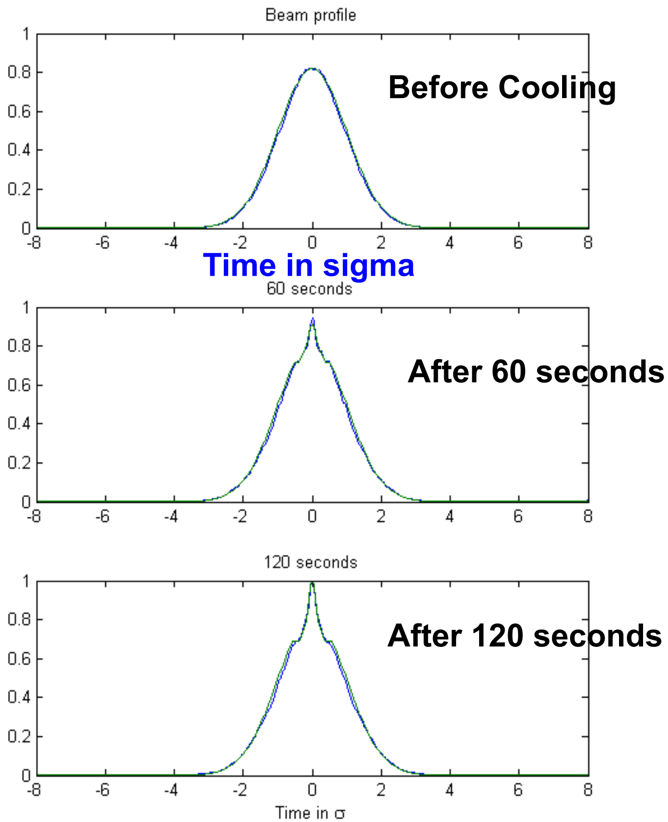


Longitudinal Schottky spectra at 4 GHz before and after stochastic cooling. Blue is reference, red is narrowed spectrum after cooling.   M. Brennan EPAC06 THPCH078

RHIC Wall Current Monitor Simulation for CeC

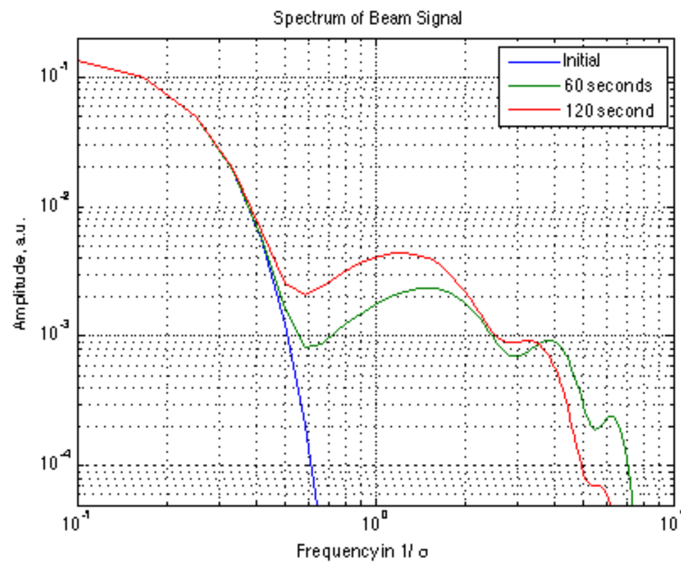


RHIC Wall Current Monitor Simulations (ideal conditions)
Au 40GeV/n, 1.5ns rms bunch length sigma, 10^9 ions/bunch
22MeV electron beam, 20ps rms, locked to center of ion bunch



Courtesy A. Fedotov

Wall Current Monitor
Simulated frequency response



0.05GHz **.5GHz** **5GHz**

Courtesy I. Pinayev

BROOKHAVEN NATIONAL LABORATORY

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U.S. DEPARTMENT OF ENERGY

December 8-10, 2014

Summary

CURRENTLY, all instrumentation for phase 1 (less loss monitors & Emittance Slit) is installed and online supporting the search for first beam.

OPEN ISSUES include:

- **Wiggler IR light diagnostics**:
  - profile & spectrum requirements are not yet defined
  - compounded by high cost solutions
- **BPM's**:
  - new electronics design with custom RF front-ends
  - ability to distinguish between ion & electrons on shared pick-up electrodes

LOOKING FORWARD, cables pulled for phases 2.1 & 3 are 90% complete and components for both phases are being assembled for installation along with loss monitors & Emittance slit for phase 2.1 in early 2015 and phase 3 in summer 2015.

We can apply experience gained at:

Energy Recovery LINAC for electron beam commissioning.
RHIC to help demonstrate coherent electron cooling for the first time.